

Enhanced diphoton Higgs decay rate and isospin symmetric Higgs boson

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The ATLAS and CMS experiments have recently discovered a new 125 GeV scalar boson. We show that the properties of this scalar, including the enhancement of its diphoton decay rate, can be naturally explained in a model with an isospin symmetric Higgs boson. The predictions of the model relevant for future experiments are also discussed.

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Introduction.— Recently, the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) reported that a new scalar boson h , compatible to the Standard model (SM) Higgs boson H , was discovered in the mass range 125–126 GeV. On the other hand, the ATLAS and CMS data might already suggest existence of a new physics beyond the SM: While the decay channels of $h \rightarrow ZZ^*$ and $h \rightarrow WW^*$ are fairly consistent with the SM, the diphoton branching ratio $\text{Br}(h \rightarrow \gamma\gamma)$ is about 1.6 times larger than the SM value¹. This deviation from the SM has been discussed by many authors [5].

In this paper, we will show that the ATLAS and CMS data for the enhanced diphoton branching ratio can be quite naturally explained in the class of models with isospin symmetric (IS) electroweak Higgs boson suggested by the authors in Refs. [6, 7]. It is noticeable that as will be shown below, these models also make several predictions, which can be checked at the LHC in the near future.

IS Higgs Models.— The main characteristics of the IS Higgs boson models are the following [6, 7]. a) It is assumed that the dynamics primarily responsible for electroweak symmetry breaking (EWSB) leads to the mass spectrum of quarks with no (or weak) isospin violation. *Moreover, it is assumed that the values of these masses are of the order of the observed masses of the down-type quarks.* b) The second (central) assumption is introducing the horizontal interactions for the quarks in the three families. As a first step, a *subcritical* (although nearcritical, i.e., strong) diagonal horizontal interactions for the top quark is utilized which lead to the observed ratio $\frac{m_t}{m_b} \simeq 40.8$. The second step is introducing *equal* strength horizontal flavor-changing-neutral (FCN) interactions between the t and c quarks and the b and s ones. As was shown in [6], these interactions naturally provide the observed ratio $m_c/m_s \simeq 11.5$ in the second family. As to the mild isospin violation in the first family, it was studied together with the effects of the family mixing, reflected in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [6]. Although the concrete model in Refs. [6, 7] utilized the fourth family of fermions [8, 9] for generating EWSB, this choice is not crucial, as the authors emphasized in [6]. In particular, the fourth family can be replaced by an elementary Higgs boson.

In this scenario, beside the EWSB interactions, the dominant dynamics responsible for the form of the mass spectrum of quarks is connected with the diagonal horizontal interactions for the third family and the horizontal, isospin symmetric, FCN interactions between the second and third ones. One of the signatures of this scenario is the appearance of a composite top-Higgs boson h_t composed of the quarks and antiquarks of the third family [6]².

Thus, the main source of the isospin violation in this approach is the strong top quark interactions. On the other hand, because these interactions are subcritical, the top quark plays a minor role in EWSB. The latter distinguishes this scenario from the top quark condensate model [11–16]. Note that unlike the topcolor assisted technicolor model (TC2) [17], this class of models utilizes subcritical dynamics for the top quark, so that the top-Higgs h_t is heavy in general. Here we also emphasize that while the top-Higgs boson h_t has a large top-Yukawa coupling, the IS Higgs

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¹ To the contrary, Plehn and Rauch [3] have recently argued that none of the measured couplings deviates from its SM values significantly. Also, the QCD uncertainties are discussed in Ref. [4]. Thus, the observed deviations are not yet definitive.

² Such composites in the nearcritical regime in a symmetric phase of models with dynamical chiral symmetry breaking were studied by several authors [10].

boson h does not, $y_t \simeq y_b \sim 10^{-2}$. On the other hand, the hWW^* and hZZ^* coupling constants are close to those in the SM (see below). Let us now describe the decay processes of the IS Higgs h .

Decay modes $h \rightarrow \gamma\gamma$, $h \rightarrow Z\gamma$, $h \rightarrow WW^$, and $h \rightarrow ZZ^*$.*— Let us consider the diphoton branching ratio in the IS Higgs model. It is well known that the W -loop contribution to $H \rightarrow \gamma\gamma$ is dominant in the SM, while the top-loop effect is destructive against the W -loop. More concretely, the diphoton partial width in the SM reads [18]:

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{\sqrt{2}G_F\alpha^2 m_H^3}{256\pi^3} \left| A_1(\tau_W) + N_c Q_t^2 A_{\frac{1}{2}}(\tau_t) \right|^2, \quad \tau_W \equiv \frac{m_H^2}{4m_W^2}, \tau_t \equiv \frac{m_H^2}{4m_t^2}, \quad (1)$$

where G_F denotes the Fermi constant, $N_c = 3$ represents the number of color, and $Q_t = +2/3$ is the electric charge of the top quark. The loop functions A_1 and $A_{1/2}$ for W and t , respectively, are given by

$$A_1(\tau) \equiv -\frac{1}{\tau^2} \left[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau) \right], \quad (2)$$

and

$$A_{\frac{1}{2}}(\tau) \equiv \frac{2}{\tau^2} \left[\tau + (\tau - 1)f(\tau) \right], \quad (3)$$

with $f(\tau) \equiv \arcsin^2 \sqrt{\tau}$ for $\tau \leq 1$. Then, the numerical values of the W - and t -loop functions read

$$A_1(\tau_W) = -8.32, \quad A_{\frac{1}{2}}(\tau_t) = 1.38, \quad (4)$$

for $m_W = 80.385$ GeV [19], $m_t = 173.5$ GeV [19], and $m_H = 125$ GeV.

On the other hand, in the IS Higgs model, the Yukawa coupling between the top and the IS Higgs h is as small as the bottom Yukawa coupling, so that the top-loop contribution is strongly suppressed. The decay width of $h \rightarrow \gamma\gamma$ is thus enhanced without changing essentially $h \rightarrow ZZ^*$ and $h \rightarrow WW^*$. A rough estimate taking the isospin symmetric top and bottom Yukawa couplings $y_t \simeq y_b \approx 10^{-2}$ is as follows:

$$\frac{\Gamma^{\text{IS}}(h \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(H \rightarrow \gamma\gamma)} \simeq 1.56, \quad \frac{\Gamma^{\text{IS}}(h \rightarrow WW^*)}{\Gamma^{\text{SM}}(H \rightarrow WW^*)} = \frac{\Gamma^{\text{IS}}(h \rightarrow ZZ^*)}{\Gamma^{\text{SM}}(H \rightarrow ZZ^*)} = \left(\frac{v_h}{v} \right)^2 \simeq 0.96. \quad (5)$$

Here using the Pagels-Stokar formula [20], we estimated the vacuum expectation value (VEV) of the top-Higgs h_t as $v_t = 50$ GeV, and the VEV v_h of the IS Higgs h is given by the relation $v^2 = v_h^2 + v_t^2$ with $v = 246$ GeV. Note that the values of the ratios in Eq. (5) are not very sensitive to the value of v_t , e.g., for $v_t = 40$ – 100 GeV, the suppression factor in the pair decay modes to WW^* and ZZ^* is 0.97–0.84 and the enhancement factor in the diphoton channel is 1.58–1.37. For the decay mode of $h \rightarrow Z\gamma$, this model yields

$$\frac{\Gamma^{\text{IS}}(h \rightarrow Z\gamma)}{\Gamma^{\text{SM}}(H \rightarrow Z\gamma)} \simeq 1.07 \quad (6)$$

(the data concerning this decay channel has not yet been reported [1, 2]). Note that the total decay width is almost unchanged, so that Eqs. (5) and (6) indicate the suppression/enhancement factors of the corresponding branching ratios.

The values in Eq. (5) agree well with the data in the ATLAS and CMS experiments. However, obviously, the main production mechanism of the Higgs boson, the gluon fusion process $gg \rightarrow h$, is now in trouble. The presence of new chargeless colored particles, which considered by several authors [21] can help to resolve this problem. We pursue this possibility below.

Model with colored scalar.— We utilize an effective theory near the EWSB scale. The model contains: (1) the IS Higgs doublet Φ_h , which is mainly responsible for the EWSB and couples to the top and bottom in the isospin symmetric way, and (2) the top-Higgs doublet Φ_{h_t} , which is required to obtain the correct top mass, (3) the colored scalar and/or fermions which are required to enhance $gg \rightarrow h$.

The items (1) and (2) above are essentially described in Refs. [6, 7]. The only difference is that the two composite Higgs doublets composed of the 4th generation quarks should be now replaced by the IS Higgs. Note that the effective theory \mathcal{L} contains the IS Higgs quartic coupling λ_h , $\mathcal{L} \supset -\lambda_h |\Phi_h^\dagger \Phi_h|^2$, and the mass $m_h = 125$ GeV corresponds to a small λ_h via the relation $m_h^2 \simeq 2\lambda_h v_h^2$ like in the SM, because the mixing between Φ_h and Φ_{h_t} in the present model is tiny (compare with Refs. [6, 7]). However, unlike the case of the SM [22], this does not imply that the theory keeps the perturbative nature up to some extremely high energy scale, as we will see below.

As to a concrete realization of item (3), we may introduce a real scalar field S in the adjoint representation of the color $SU(3)_c$ and utilize the Higgs-portal model [21], just as a benchmark case:

$$\mathcal{L} \supset \mathcal{L}_S = \frac{1}{2}(D_\mu S)^2 - \frac{1}{2}m_{0,S}^2 S^2 - \frac{\lambda_S}{4} S^4 - \frac{\lambda_{hS}}{2} S^2 \Phi_h^\dagger \Phi_h, \quad \Phi_h = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(v_h + h + iz_0) \end{pmatrix}, \quad (7)$$

where ω^\pm and z_0 are the components eaten by W^\pm and Z . The scalar field S is chosen to be assigned to the $(\mathbf{8}, \mathbf{1})_0$ representation of the $SU(3)_c \times SU(2)_W \times U(1)_Y$. Other representations, for example, a color triplet, are also possible. Note that we do not incorporate a Higgs-portal term between S and Φ_{h_t} and other possible cubic and quartic terms into Eq. (7), because they do not have any important role in the following analysis.

The mass-squared term for the scalar S is given by

$$M_S^2 = m_{0,S}^2 + \frac{\lambda_{hS}}{2} v_h^2, \quad (8)$$

and should be positive in order to avoid the color symmetry breaking. Typically, $M_S \sim 200$ GeV is allowed in the current data [21]. We will take a positive value for λ_{hS} and a classically (quasi-)scale invariant model with $m_{0,S}^2 \approx 0$, which is favorable to reproduce the SM like gluon fusion production.

Let us consider the contribution of the color octet S to the gluon fusion process $gg \rightarrow h$ in the leading order:

$$\frac{\sigma(gg \rightarrow h)}{\sigma^{\text{SM}}(gg \rightarrow H)} \sim \frac{\Gamma(h \rightarrow gg)}{\Gamma^{\text{SM}}(H \rightarrow gg)} = \left| \frac{C_A \lambda_{hS} \frac{vv_h}{2M_S^2} A_0(\tau_S)}{A_{\frac{1}{2}}(\tau_t)} \right|^2, \quad (9)$$

with $C_A = 3$, $\tau_S \equiv m_h^2/(4M_S^2)$, and

$$A_0(\tau) \equiv -\frac{1}{\tau^2} \left[\tau - f(\tau) \right]. \quad (10)$$

We find $A_0 \simeq 0.37\text{--}0.34$ for $M_S = 150\text{--}400$ GeV, so that an appropriate value of the Higgs-portal coupling is

$$\lambda_{hS} \simeq 2.5\text{--}2.7 \times \frac{M_S^2}{vv_h}. \quad (11)$$

As a typical value, we may take $\lambda_{hS} = 1.8$ for $M_S = 200$ GeV and $v_t = 50$ GeV. When $m_{0,S}^2 \approx 0$, i.e., $M_S^2 \approx \lambda_{hS} v_h^2/2$, we obtain $\Gamma(h \rightarrow gg) \approx 0.6 \times \Gamma^{\text{SM}}(H \rightarrow gg)$, independently of the values of λ_{hS} . In order to stabilize the Higgs potential for S at the tree level, the relation $|\lambda_{hS}| < 2\sqrt{\lambda_S \lambda_h}$ is also required.

A comment concerning the IS Higgs quartic coupling λ_h is in order. In the SM, the Higgs mass 125 GeV suggests that the theory is perturbative up to an extremely high energy scale [22]. On the contrary, in the present model, when we take a large Higgs-portal coupling λ_{hS} that reproduces $gg \rightarrow h$ correctly, the quartic coupling λ_h will grow because the β -function for λ_h contains the λ_{hS}^2 term. Also, there is no large negative contribution to the β -function for λ_h from the top-Yukawa coupling $y_t \sim 10^{-2}$.

One can demonstrate such a behavior more explicitly by using the renormalization group equations. In Fig. 1, the running of the coupling λ_h is shown. The IS Higgs mass is $m_h = \sqrt{2\lambda_h} v_h$, and we take it to be equal 125 GeV. Taking a large Higgs-portal coupling $\lambda_{hS} = 1.8$ and the S^4 -coupling $\lambda_S = 1.5$, it turns out that the coupling λ_h rapidly grows. Due to the running effects, the naive instability of the scalar potential at the tree level is resolved around the TeV scale in this case. The blowup scale strongly depends on the initial values of λ_{hS} and λ_S . A detailed analysis will be performed elsewhere.

Conclusion.— The model with an IS Higgs boson yields not only a natural explanation of the ATLAS and CMS data, including the enhanced diphoton Higgs decay rate, but also makes several predictions. The most important of them is that the value of the top-Yukawa coupling $h\text{--}t\text{--}\bar{t}$ should be close to the bottom-Yukawa one. Another prediction relates to the decay mode $h \rightarrow Z\gamma$, which unlike $h \rightarrow \gamma\gamma$ is enhanced only slightly, $\Gamma^{\text{IS}}(h \rightarrow Z\gamma) = 1.07 \times \Gamma^{\text{SM}}(H \rightarrow Z\gamma)$. Last but not least, the LHC might potentially discover a heavy top-Higgs resonance h_t .

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[1] ATLAS Collaboration, arXiv:1207.7214 [hep-ex].

[2] CMS Collaboration], arXiv:1207.7235 [hep-ex].

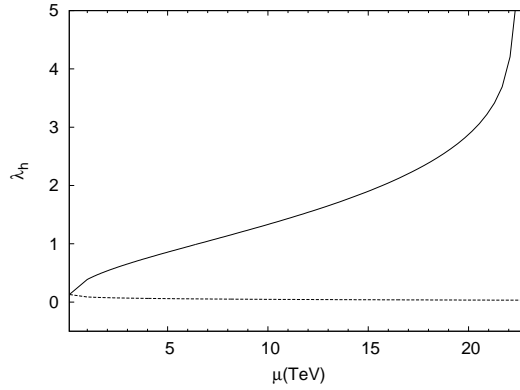


FIG. 1: The running behavior of the IS Higgs quartic coupling λ_h . The solid and dashed lines correspond to λ_h and the SM Higgs quartic coupling, respectively. We fixed the IS Higgs mass $m_h = \sqrt{2\lambda_h}v_h = 125$ GeV and took $\lambda_{hS} = 1.8$ and $\lambda_S = 1.5$. Unlike the SM, the IS Higgs quartic coupling grows up due to a large Higgs-portal coupling λ_{hS} and a small top-Yukawa coupling y_t .

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